KineMa

Numerical Modeling of Kinetic Magnetized Plasmas

April 3rd-7th 2017
IESC, Cargèse

PROGRAM

Preliminary program (as of April 2)

times	Monday 4/3	Tuesday 4/4	Wednesday 4/5	Thursday 4/6	Friday 4/7
8h50 - 9h20	Eric Sonnendrücker Introduction to Finite Element Exterior Calculus	Eric Sonnendrücker A discrete variational framework for the Vlasov-Maxwell equations	Eric Sonnendrücker Modern gyrokinetic theory and its implementation	Giovanni Manfredi Kinetic modelling of the plasma-wall transition in magnetized fusion plasmas	
9h20 - 9h50					Shi Jin Uncertainty quantification in kinetic equations
9h50 - 10h20					Michael Kraus Discontinuous Galerkin Variational Integrators for Degenerate Lagrangians
10h20-10h40	break	break	break	break	break
10h40 - 11h10	Josh Burby Discrete collisionless kinetics: how far we've come and where we're going	Josh Burby Discrete collisionless kinetics: how far we've come and where we're going	Josh Burby Discrete collisionless kinetics: how far we've come and where we're going	Mohammed Lemou Averaging techniques and uniformly accurate numerical approximations of Vlasov equations with strong magnetic field	
11h10- 11h40					
11h40 - 12h10					
12h10-13h40	lunch	lunch	lunch	lunch	SHUTTLE IESC > AJA
13h40-14h10	Hélène Hivert An AP scheme for a kinetic equation describing propagation phenomena	Andreas Stegmeir Flux-Coordinate Independent approach		Giovanni Manfredi Kinetic modelling of the plasma-wall transition in magnetized fusion plasmas	
14h10-14h40	Maxime Herda Derivation of hydrodynamic models for massless electrons in magnetized plasmas	Mihai Bostan Averaging methods for particle systems			
14h40 - 15h10	Mehdi Badsi Drift asymptotic schemes for the Euler-Lorentz system	Stéphane Heuraux Simulations on wave propagation in magnetized plasmas inducing questions in special cases: large areas with null refractive index, resonance amplification in white noise, bad evolution of the computation time for very large values of the refractive index			
15h10 - 15h30	break	break	break	break	
15h30 - 16h	Francis Filbet On the asymptotic limit of the three dimensional Vlasov-Poisson system for large magnetic field	Cesare Tronci Modeling efforts in hybrid kinetic-MHD systems		Mohammed Lemou Averaging techniques and uniformly accurate numerical approximations of Vlasov equations with strong magnetic field	
16h - 16h30	Stefan Possanner Finite-order guiding-center transformations from algebraic equations				
16h30 - 17h					
	19h: Welcome drink (IESC)			Social dinner (IESC)	

Abstracts of lectures

▷ Josh Burby (Courant Institute, New York)
Discrete collisionless kinetics: how far we've come and where we're going
Collisionless kinetic models typically possess Hamiltonian structure that is inherited from an underlying many-body problem. This Hamiltonian structure is responsible for many of the "conservative" properties that these models enjoy. Recently, a number of researchers have uncovered continuous-time particle-in- cell discretizations of collisionless kinetic models that retain the Hamiltonian structure of their parent continuum model. I will discuss this work using a tutorial-style approach. Then I will introduce and speculate about two important open problems in the area of structure-preserving discretization of kinetic models.

▷ Mohammed Lemou (CNRS IRMAR, Rennes)
Averaging techniques and uniformly accurate numerical approximations of Vlasov equations with strong magnetic field

- *Part I: Averaging techniques for highly oscillatory transport equations*
  We will first present some methods in the literature which are designed to derive asymptotic models from Vlasov equations with strong magnetic field. Then we come to the first goal of this first part, which is to present a new strategy that allows a systematic derivation of high order averaging models with a complete recovery of the distribution function. The method will be presented in the general context of highly oscillatory transport equations: more precisely, we will show that a combination of standard averaging techniques with an equation on a suitably chosen oscillation phase, allows one to achieve this goal. We finally show how the methodology can be applied, not only to the case of Vlasov equation with constant magnetic field, but also to the case where this field has a non trivial space dependence. A particular attention will be paid to gyrokinetic asymptotics of Vlasov equation.

- *Part II: Uniformly accurate numerical approximations of Vlasov equation with strong magnetic field*
  We first present the usual strategy to get numerical schemes having the so called asymptotic preserving property. In the strong magnetic field limit, these approximations degenerate into numerical schemes which are consistent with the averaged models. We then show how to go beyond this property and get numerical schemes with uniform accuracy. In particular a suitable two-scale reformulation will be presented in detail, which is at the heart of the construction of uniformly accurate numerical schemes. In this way, one may capture oscillations in the system without resolving the high frequencies, and in particular the accuracy of these numerical schemes is uniform with respect to the oscillation frequency. Some numerical experiments will finally be presented to illustrate the efficiency of the above strategy, mainly in the framework of a gyrokinetic scaling of kinetic equations.

▷ Giovanni Manfredi (CNRS IPCMS, Strasbourg)
Kinetic modelling of the plasma-wall transition in magnetized fusion plasmas
The vast majority of plasmas produced in the laboratory are in contact with a material surface. In fusion devices, the surface can be either the material vessel that contains the plasma, or some *ad-hoc* device (limiter or divertor) specifically designed to optimize the interaction with the charged particles. These surfaces are eroded by ion and neutral bombardment and may thus see their lifetime considerably reduced. In addition, plasma-wall interactions also affect the outcome of probe measurements, as the probe's surface can disturb the plasma characteristics. Perhaps the main feature of the physics of plasma-wall interactions is the formation of *sheaths*, i.e., boundary layers

that form at the interface between the plasma and the surface. In a tokamak, the sheaths must support the main share of particles and heat fluxes directed towards the divertor. In these seminars, I will review the basic theoretical and computational aspects of plasma- wall interactions. Some fundamental results will be derived analytically using a simple fluid model, and subsequently tested with kinetic simulations. The various regions com- posing the plasma-wall transition will be discussed in detail. The structure of the plasma-wall transition is considerably modified by the presence of a magnetic field, particularly when the latter has a grazing incidence with respect to the surface. Here, I will describe the angular and energy distribution of the ions impinging on the surface, which is an important parameter to determine the level of wall erosion and sputtering. Finally, I will discuss some transient (i.e., time-dependent) phenomena, such as the par- allel transport of energetic charged particles in a tokamak edge following an ELM (edge- localized mode) event. Recent attempts to model these effects by means of kinetic equa- tions will be illustrated and discussed.

▷ Eric Sonnendrücker (TUM and Max-Planck IPP, Garching)

- *Part I: Introduction to Finite Element Exterior Calculus*
  In this lecture we will introduce the geometrical concepts needed for Finite Element Exterior Calculus, the theory introduced by Arnold, Falk and Winther for the discretization of differential forms. We will in particular introduce the notions of manifolds, tangent vectors, differential forms, wedge product, interior product, pullback, metric and a scalar product for differential forms and show how they can be discretized using the Finite Element concept. This will lead to a discrete Hilbert complex of differential forms that can be reproduced at the discrete level yielding natural stability properties. We will also see how Finite Element spaces of differential forms relate to more classical finite element spaces. We will focus on spline based Finite Element, which are in particular used in isogeometric analysis and very convenient for the coupling with particle methods for the Vlasov equation.
- *Part II: A discrete variational framework for the Vlasov-Maxwell equations*
  Starting either from the action principle proposed by Low or the non canonical hamiltonian formulation of the Vlasov-Maxwell system by Morrison, Marsden and Weinstein, we shall show that using a particle discretization of the Vlasov equation and a compatible Finite Element approximation of Maxwell's equations based on Arnold, Falk and Winther's Finite Element Exterior Calculus, the semi-discrete equations form a finite dimensional Poisson system, which is the non canonical extension of a symplectic system. This system features Casimir invariants, which are the Gauss law and div B, as well as energy and momentum conservation, which yields enhanced stability properties compared to standard Particle In Cell codes. The derivation and analysis of the discrete system will be presented as well as numerical results illustrating its properties.
- *Part III: Modern gyrokinetic theory and its implementation*
  The Vlasov-Maxwell equations can be derived from an action principle, which allows to derive conservation laws from symmetries of the Lagrangian. Gyrokinetic theory is an asymptotic reduction of the Vlasov-Maxwell equations in the presence of a large magnetic field. What is called modern gyrokinetic theory, following Brizard, Qin, Scott, Sugama and others, aims at retaining the same structure. More precisely, starting from the Vlasov-Maxwell Lagrangian consisting of a particle and a field part, the asymptotic reduction is performed on the single particle Lagrangian via a series of near identity coordinate transforms, called Lie transforms, and possibly on other terms of the Lagrangian. Then the gyrokinetic equations are derived as the Euler-Lagrange equations of the modified Lagrangian without further approximations. This yields gyrokinetic conservation laws, which can be compared to the Vlasov-Maxwell conservation laws. In this lecture we will introduce the derivation of modern gyrokinetic theory detailing a few of its variants and see how this can be related to models implemented in actual gyrokinetic codes. A code verification effort based on this theory will also be presented.

Short presentations

▷ Mehdi Badsi (MIP IMT, Toulouse)
Drift asymptotic schemes for the Euler-Lorentz system.
We shall introduce the Euler-Lorentz system which is a fluid description of magnetized plasmas and discuss related numerical difficulties. In the strong magnetic field limit, the momentum equation degenerates into a force balance between the pressure gradient and the Lorentz force. The parallel momentum equation becomes singular. Therefore the computation of the parallel velocity is more intricate. We shall address this difficulty in the specific context of the electron adiabatic response by considering a simplified model of the parallel dynamic. We present a finite volume discretization of this model based on staggered grids. The scheme is consistent in the strong magnetic field limit and preserves the positivity of the pressure.

▷ Mihai Bostan (LATP, Marseille)
Averaging methods for particle systems
The averaging methods play a crucial role when studying the dynamics of particle populations. Among the main applications, we mention the magnetic confinement, which concerns the transport of charged particles under strong magnetic fields. The main tool is the average operator along a characteristic flow. Another application is the study of self-propelled swarming systems, whose particles are interacting through large propulsion and friction forces. We present an asymptotic analysis for such models, following closely the gyro-average technique used when studying the gyrokinetic models.

▷ Francis Filbet (MIP IMT, Toulouse)
On the asymptotic limit of the three dimensional Vlasov-Poisson system for large magnetic field
We establish the asymptotic limit of the three dimensional Vlasov–Poisson equation with strong external magnetic field. The guiding center approximation is investigated in the three dimensional case with a non-constant magnetic field. In the long time asymptotic limit, the motion can be split in two parts : one stationary flow along the lines of the magnetic field and the guiding center motion in the orthogonal plane of the magnetic field where classical drift velocities and invariants (magnetic moment) are recovered.

▷ Maxime Herda (ICJ, Lyon)
Derivation of hydrodynamic models for massless electrons in magnetized plasmas

▷ Stéphane Heuraux (P2M IJL, Nancy)
Simulations on wave propagation in magnetized plasmas in special cases: $N = 0$, resonance amplification in white noise, computations with large refractive index variations and . . .
The presentation is focused on simulations, that asks questions about the validity of the numerical results. The guideline comes from a simple test case devoted to Maxwell's equations solver for which a homogeneous plasma is defined to fulfil the condition N=0 where N is the refractive index of this medium. The expected behaviour of the wave electric field obtained with a Laplace equation should be linear and exhibits always variations in time. To know why, some Dirac's mass with very low amplitude were added to see if we can recover similar shapes with a wave equation solver. Different spatial distributions of the Dirac's masses will be presented, finishing with a random distribution between -ε and ε giving again the linear behaviour as the standard solution. Now a new question appears what the impact of a white noise on the wave-electric field simulations? To test this, a resonance is a good candidate due the fact that a resonant condition is very sensitive to any perturbation. Thus a resonant condition was established and a white noise added to the refractive index. Analysing it, we see that the quality factor of the cavity was enhanced and increases non-linearly

as function of the white noise level. To do that an extended precision is required for tuning the resonance at its maximum. After this excursion around $N = 0$ we look at the impact of large variation of the refractive index. The study of such test cases was built based on the extraordinary mode in magnetized plasma. Using well-defined plasma density and magnetic field intensity profiles, the refractive index is able to reach high refractive index values. It is possible to reduce the group velocity by 2 orders of magnitude. As a consequence the computation time increases by 100. How to improve the computation time is open question. To finish PIC code simulations are shown, mentioning that Poisson's equation looks like the test cases with the Dirac's masses, and we conclude by addressing questions to the participants.

▷ Hélène Hivert (UMPA, ENS Lyon)
An AP scheme for a kinetic equation describing propagation phenomena

▷ Shi Jin (University of Madison)
Uncertainty quantification in kinetic equations

▷ Michæl Kraus (Max-Planck IPP, Garching)
Discontinuous Galerkin Variational Integrators for Degenerate Lagrangians

▷ Stefan Possanner (Max-Planck IPP, Garching)
Finite-order guiding-center transformations from algebraic equations

▷ Andreas Stegmeir (Max-Planck IPP, Garching)
Flux-Coordinate-Independent approach
The complex geometry in the edge and scrape-off layer poses a challenge to simulations of magnetically confined plasmas. The usually employed field/flux- aligned coordinates become singular on the separatrix/X-point. The Flux-Coordinate- Independent (FCI) approach constitutes a promising solution to these problems. The approach is based on a cylindrical grid which is Cartesian within poloidal planes, and the strong anisotropy of structures is exploited computationally via grid sparsification in the toroidal direction. A field line following discretisation for parallel operators is applied, which includes field line tracing and interpolation or integration. The seperatrix and X-point(s) are thereby handled without any special treatment. A conservative formulation of FCI, based on staggered grids will be presented, which reduces numerical diffusion drastically and establishes the basis for numerical conservation of energy. Moreover, the treatment of boundary conditions, a subtle but critical issue within the FCI, will be discussed. Examples and application of the FCI will be shown via the 3D turbulence code GRILLIX, which is based on a drift reduced fluid model. Possibilities for application of the FCI in a kinetic framework will be discussed.

▷ Cesare Tronci (University of Surrey)
Modeling efforts in hybrid kinetic-MHD systems
Over the decades, multiscale modeling efforts have resorted to powerful methods, such as asymptotic/perturbative expansions and/or averaging techniques. As a result of these procedures, finer scale terms are typically discarded in the fundamental equations of motion. Although this process has led to well consolidated plasma models, consistency issues may emerge in certain cases especially concerning the energy balance. This may lead to the presence of spurious instabilities that are produced by nonphysical energy sources. The talk proposes alternative techniques based on classical mechanics and its underlying geometric principles. Inspired by Littlejohn's guiding-center theory, the main idea is to apply physical approximations to the action principle (or the Hamiltonian structure) underlying the fundamental system, rather than operating directly on its equations of motion. Here, I will show how this method provides new energy-conserving variants of hybrid kinetic-MHD models, which suppress the spurious instabilities emerging in previous non-conservative schemes.

Participants

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